Risk Based Reservoir Operation

J. R. Hansford[1], B. Mwaka[2]

[1] Knight Piésold Consulting, Johannesburg, South Africa
[2] Department of Water Affairs and Forestry, Pretoria, South Africa

ABSTRACT

As water demands increase more and more water supply systems are becoming stressed. Accordingly, to avoid failure of the water resource system, supply to users will have to be restricted during periods of drought. Restricting users too much will result in economic loss while restricting too little will result in failure of the water resource. Consequently the operator needs to know with confidence how much water can be supplied to users.

The need for an easy to use tool that the reservoir operator can use to allocate water for the next year and also to assist the operator in showing the consequences of deviating from the rule is obvious.

As part of a project for DWAF the *Reservoir Operation Model* (*ROM*) was developed in 2003 and implemented for eight reservoirs in KwaZulu-Natal. In 2004 the model was implemented for a further 22 reservoirs. *ROM* utilises short-term yield curves to calculate how much water can be allocated to users during the next year at the desired assurance. The model also includes the facility to plot projected storage in the reservoir. This allows the operator to demonstrate to the users the risk of the reservoir drawing empty if the calculated allocation of water is supplied and also how the risk will change if additional water is supplied.

The paper describes the theory used in the model and demonstrates how the model can be used to make risk based decisions on water supply from a reservoir.

Keywords: *Reservoir operation*

1 INTRODUCTION

In many parts of the world the water requirements of users have grown until the resources are no longer adequate to meet the requirements without shortfalls during periods of drought. Under these conditions the operators need to be able to make decisions as to how much they need to restrict water supply to the users to avoid total failure of the system but without imposing unnecessarily harsh restrictions that would have an adverse economic impact on the users.

Typically decisions are made annually and are based on the results of analyses using short-term inflow sequences. Models used for the analyses require specialist input to ensure that the input to the model is correct and to interpret the results. The advantage of a model that could be set up by specialists and then used by the operator to make decisions on supply to users is obvious.

The *Reservoir Operation Model* (*ROM*) was developed for the Department of Water Affairs and Forestry (DWAF) specifically to meet this need. Initial development of the model was done in 2003 as part of project to develop operating rules for 8 dams in KwaZulu-Natal. After this project the model was set up for another 22 dams located in various provinces in South Africa. Further enhancements have been made and will continue to be made so that the model meets the operator requirements.

2 DESCRIPTION OF THE *ROM*

ROM was developed to provide a tool that could be used to make risk based decision as to how much water could be supplied to users during the next year. A further requirement was that the model should be simple to use so that it could be run by reservoir operators so that they did not need to refer to DWAF Head Office or consultants every time operating decisions needed to be made. To meet these requirements *ROM* was developed to:

- Determine from the results of short-term yield analysis how much water could be supplied at the desired assurance to users during the next year;
- Maintain a log file containing summary results for each analysis;
- Calculate how this water would be distributed between users and
- Display the projected trajectory of storage in the reservoir if this water is supplied.

The *ROM* runs under Windows 95, 98, NT or XP operating systems. The start up screen is shown in Figure 1.

The user selects the reservoir for analysis, the decision month hydrology and current storage state and then clicks on the analyse button. *ROM* calculates and displays the allowable supply from the reservoir together with the demand on the reservoir.

Selecting the "Assurance demands" tab (Figure 2) displays the total demand on the reservoir according to assurance categories and the Priority Classification Table used to allocate water to users.

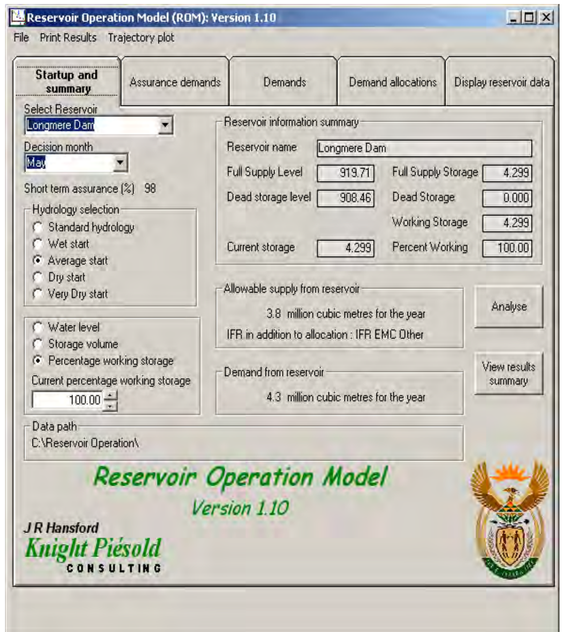


Figure 1: *ROM* startup screen

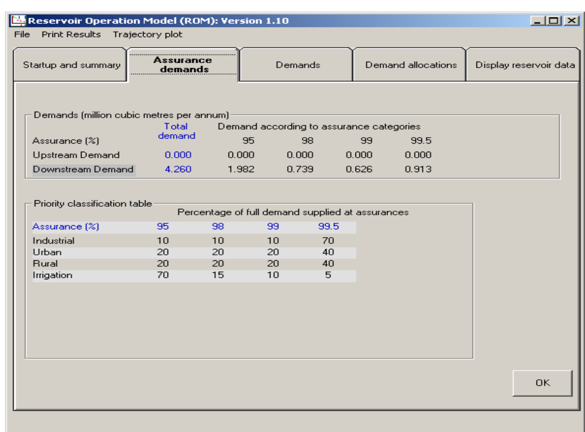


Figure 2: *ROM* "Assurance demands" screen

The total demand, in accordance with the Priority Classification Table, is displayed so that the user can see at a glance the demand for each assurance category. The Priority Classification Table shows the distribution of the demand between the assurance categories for each class of user.

The demand screen (Figure 3) shows all demands that can be supplied from the reservoir. Demands that the operator intends to supply from the reservoir are checked and the percentage of the checked demands can also be selected. This is applicable to demands that can be supplied from more than one source. Changes made by the operator are not made to the input data file but are saved separately so that the same changes do not have to be made every time the reservoir is analysed.

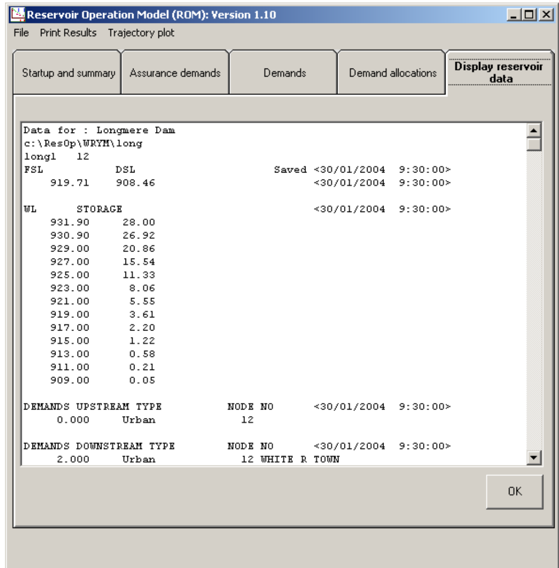


Figure 3: *ROM* Demand screen

The “Demand Allocation” screen (Figure 4) displays the demands the allocation to each user according to the Priority Classification Table.

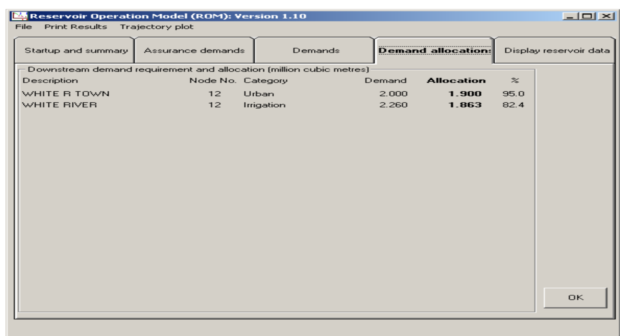


Figure 4: *ROM* Demand allocation screen

The reservoir input data file can be viewed by selecting the “display reservoir data” screen (Figure 5).

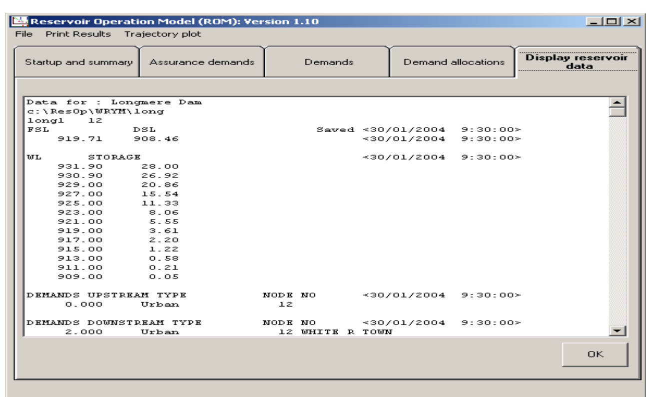
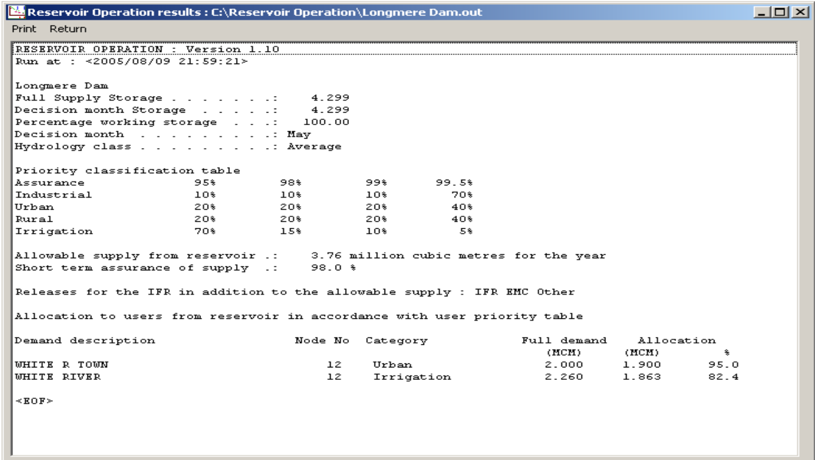


Figure 5: *ROM* Display Reservoir data screen

A summary of the analysis results (Figure 6) can be displayed by clicking on the “View results summary” button.


Reservoir Operation results : C:\Reservoir Operation\Longmere Dam.out

Print Return

```
RESERVOIR OPERATION : Version 1.10
Run at : <2005/08/09 21:59:21>

Longmere Dam
Full Supply Storage . . . . . . .:     4.299
Decision month Storage  . . . . .:     4.299
Percentage working storage  . . .:   100.00
Decision month  . . . . . . . . .: May
Hydrology class . . . . . . . . .: Average

Priority classification table
Assurance              95%        98%        99%      99.5%
Industrial             10%        10%        10%        70%
Urban                  20%        20%        20%        40%
Rural                  20%        20%        20%        40%
Irrigation             70%        15%        10%         5%

Allowable supply from reservoir .:     3.76 million cubic metres for the year
Short term assurance of supply  .:     98.0 %

Releases for the IFR in addition to the allowable supply : IFR EMC Other

Allocation to users from reservoir in accordance with user priority table

Demand description                   Node No  Category            Full demand    Allocation
                                                                     (MCM)       (MCM)        %
WHITE R TOWN                              12    Urban                2.000       1.900      95.0
WHITE RIVER                               12    Irrigation           2.260       1.863      82.4

<EOF>
```

Figure 6: ***ROM*** **summary results**

The summary results are automatically saved to file and can be sent to the printer.

Selecting “Trajectory plot” from the menu allows the user to plot projected reservoir storage or water level. The default target draft is the calculated allowable supply from the reservoir. The user can change this value, a useful feature if the operator wants to show how increasing the allowable supply will affect the risk of the reservoir drawing empty.

The reservoir trajectory can be plotted as lines for selected assurances or as the traditional box plots. An example of the trajectory plot display is shown in Figure 7.

The trajectory plot can be captured to the clipboard and the summary output is automatically saved to a text file for capture into a report. Each time the “Analyse” button is pressed an entry is written to the log file listing the reservoir name, storage, assurance and allowable supply. This log file cannot be lost, even if the software is uninstalled, so a permanent record is kept of all operating decisions.

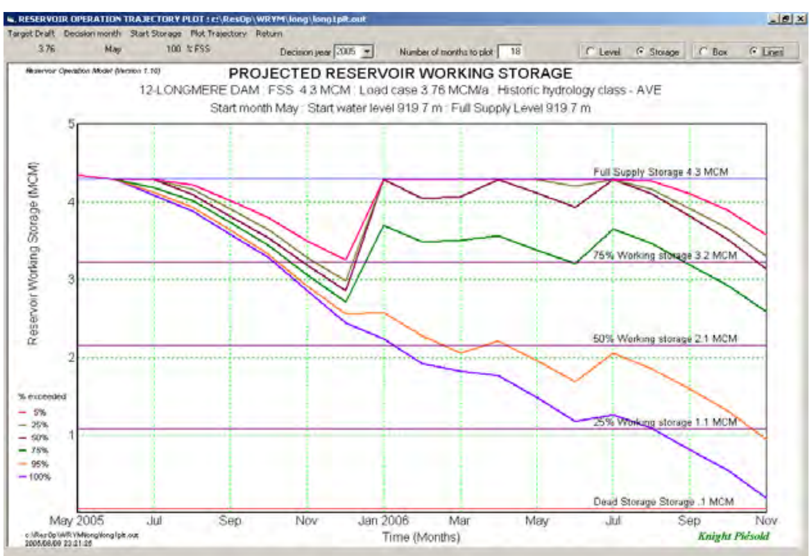


Figure 7: ***ROM*** **Trajectory Plot**

3 *ROM* INPUT DATA FILE

ROM uses an input data file that contains:

- Elevation-storage relationship for the reservoir;
- Water demands that can be supplied from the reservoir;
- Priority classification table used to allocate water to users during restrictions;
- The desired assurance of supplying water in the short-term and
- Short-term yield equations for a range of starting storage and for selected hydrologies.

The input file is a formatted text file. *ROM* includes a routine to facilitate capture of the input data. Date stamps are included in the data as a reference to when the data was changed.

Elevation-storage relationship
The same elevation-storage relationship and full supply and dead storage levels as used in the WRYM short-term stochastic analysis should be entered in the *ROM* data file.

Water demands
All water demands that can be supplied from the reservoir should be entered. The operator selects from a list the demands that are intended to be supplied from the reservoir and also the percentage of these demands to be supplied. This information is used to allocate water to users from the allocatable quantity.

Priority Classification Table
The Priority Classification Table gives the percentage of the demand supplied at a range of assurances for each category of user. The table needs to be agreed with the users.

Desired assurance of supply
This is the short-term assurance of supply and is different from the long-term assurances. It is the assurance that the reservoir will be able to supply the allocatable water over the next year.

Short-term yield curve equations and hydrology
Short-term yield curves are used by *ROM* to calculate for the desired assurance the quantity of water that can be allocated to users. Curves are required for a range of starting storage between 100% and 0% full. *ROM* can also be used with forecasting hydrology. Accordingly the short-term yield curve for all the categories of historic hydrology need to be determined. The short-term yield curves are input as the coefficients of the yield curve equations.

4 METHODOLOGY

The *ROM* utilises pre-determined short-term yield curves to determine a safe level of draft given the time of year (season) and storage in the reservoir.

Short-term reservoir yield curves need to be determined for all calendar months in which operating decisions are made and starting storage of 100, 80, 60, 40, 20 and 0 percent of working storage by simulation. When the yield from the empty dam is zero for assurances less than 99.5% an additional starting storage should be included that gives a yield at 99.5% assurance close to 0. This improves the reliability of interpolation. Simulations can be done using WRYM with 201 stochastic inflow sequences each typically 5-years long for standard stochastic hydrology, but limited to 2-year long sequences when forecasting hydrology is used (confidence in forecasting hydrology). The simulations are done for target drafts with assurances of the firm yield ranging from 95% to 99.5%. The coefficients in the equations defining the short-term yield curves are then stored in the reservoir data file and used by *ROM* to calculate the yield at the desired assurance.

The short-term yield for assurance A is calculated from the following equation:

$$\text{Short-term yield} = C_3 * P^3 + C_2 * P^2 + C_1 * P + C_0 \qquad \text{million m}^3 \text{ for the year}$$

Where $P = 100\,(A/100)^N$ the percentage of sequences without failure
N = length of short-term sequences in years
A = short-term assurance of supply as a percentage and
C_n = short-term yield curve equation coefficients.

The assurance for the short-term yield calculation is set in the reservoir data file. The default assurance value is 99.5% and can be adjusted if a lower assurance of short-term yield is considered appropriate.

ROM uses the yield equations to calculate the yield for the user selected decision month (analysis start month) for the analysed starting storage above and below the storage in the reservoir entered by the operator and interpolates linearly between these values to determine the allowable draft from the reservoir at the desired assurance.

The priority classification table defines the percentage of each user's water demand that will be supplied for a range of assurance categories. On the basis of this table the program calculates the total demand for each assurance category. The allowable yield is then allocated to the assurance categories starting with the highest assurance first, then the next level and so on until either all demands are fully supplied or the demand for an assurance category cannot be fully supplied. The percentage of the demand for that assurance category is then applied to that portion of each user's demand to determine the allocation to each user.

The program allows the short-term curves to be entered for selected months only. However, it is preferable to include the curves for all calendar months in the data file as this allows the operator to assess performance of the reservoir on a monthly basis. This is especially important if operating decisions are made on the basis of a fairly low assurance yield (say 95%). Assessing the situation monthly will allow the operator to monitor system performance and reduce drafts if the system situation deteriorates.

Short-term curves can be entered for five categories of hydrology namely:

- Standard hydrology – standard annual stochastic sequences generated using WRYM.
- Wet hydrology – forecasting monthly stochastic generator seeded with typical wet inflows.
- Average hydrology - forecasting monthly stochastic generator seeded with typical average inflows.
- Dry hydrology - forecasting monthly stochastic generator seeded with typical dry inflows and
- Very dry hydrology - forecasting monthly stochastic generator seeded with typical driest inflows.

5 ALLOCATION TO USERS

The frequency and severity of restrictions that the various user categories can tolerate varies. Some industrial users can only tolerate a fairly small reduction in water supply before production is severely affected whereas usually irrigators can tolerate fairly severe restrictions from time to time without significant losses. Accordingly users do not require all their water at the same assurance. A user priority classification table can be prepared that defines how water is distributed between the various assurance categories for each category of user. The priority classification table should be agreed with the users as it will form the basis for allocating water during droughts. A typical user priority classification table is shown in Table 1.

Allocation of the short-term allowable yield is done in accordance with the priority classification table. All priority 1 volumes are supplied first. Supply is then allocated to priority 2, 3 etc. volumes until the water runs out. How this is done in the program is best described with reference to a worked example.

Table 1: Typical user priority classification table

User category	Percentage of demand supplied at assurance			
	95%	98%	99%	99.5%
Wet industry	0	20	10	70
Industry	20	20	20	40
Urban	20	20	20	40
Rural	0	30	30	40
Irrigation	70	10	10	10
Priority of supply	4	3	2	1

Example: Allocation of allowable yield to users

Suppose the total demand from a reservoir is 33 million m^3/a, but the allowable short-term yield only 16 million m^3 for the year and there are three users that this water has to be distributed between in accordance with the priority classification table shown in table1.

The calculations to distribute the water between the users are shown in Table 2, with a description of the calculations following the table.

Table 2: Tabulated calculations for distributing water allocation to users

Column	A	B	C	D	E	F	G
Row	User	Full demand (million m^3/a)	Demand supplied at each level of assurance				Allocation (million m^3)
			95%	98%	99%	99.5%	
1	Urban	5	1.0	1.0	1.0	2.0	3.565
2	Industrial (Wet)	8	0.0	1.6	.8	5.6	7.304
3	Irrigation	20	14.0	2.0	2.0	2.0	5.130
4	TOTAL	33	15.0	4.6	3.8	9.6	15.999
5	Sums		33.0	18.0	13.4	9.6	
6	% supplied		0.0	56.5	100	100	
	Comment			Total > 16 therefore % supplied (16-13.4)/4.6	Total < 16 therefore 100% supplied		15.999 close enough to 16

In Table 2 rows 1, 2 and 3 show the information for the three users. Column B lists the full demand and columns C, D, E, and F show these demands distributed according to the percentages in the priority classification table (Table 1). Row 4 shows the total demand from the reservoir (column B) and the total demand for each assurance category (columns C, D, E and F). Row 5 shows the cumulative total demand for each assurance category i.e. the total demand at that or higher assurance. Row 6 shows the percentage of the demand for each assurance category that can be supplied. This percentage will be 100 % as long as the cumulative demand in row 5 is less than the allowable yield (columns E and F). Column D is not 100 % because the cumulative demand is greater than the allowable yield. The demand at this assurance is 4.6 million m^3, but only 2.6 million m^3 (16 - 13.4) is available. Accordingly the percentage that can be supplied for this assurance category is 56.5 %. Clearly the percentage that can be supplied to the 95% assurance category is zero. Column D shows the allocation to each user and is the sum of the demand at each assurance level multiplied by the percentage calculated in row 6.

6 TRAJECTORY PLOTS

ROM shells to WRYM to calculate the projected reservoir trajectory. This serves two purposes. Firstly the trajectory is based on simulations using the allowable supply or user defined supply to users as the target draft and secondly the trajectory plot serves as a check on the analysis done by *ROM*. The program only shells to WRYM if the analysis has not been done already. Thus the user can toggle between displaying the trajectories as lines or box plots without waiting for the WRYM analysis to be completed. Depending on the computer being used and the size of the system the WRYM simulation does delay displaying the trajectory plot.

7 CONCLUSIONS

The *ROM* has been designed to meet user requirements. It is a useful tool that enables the reservoir operator to make decisions regarding how much water can be supplied to users during the next year. The results are based on yield analyses results carried out using the well accepted WRYM. The projected reservoir trajectories both serve to show users how storage is likely to change in the future for the selected target draft and also to show the validity of the analysis result. Accordingly *ROM* can be used with confidence to make short-term operating decisions